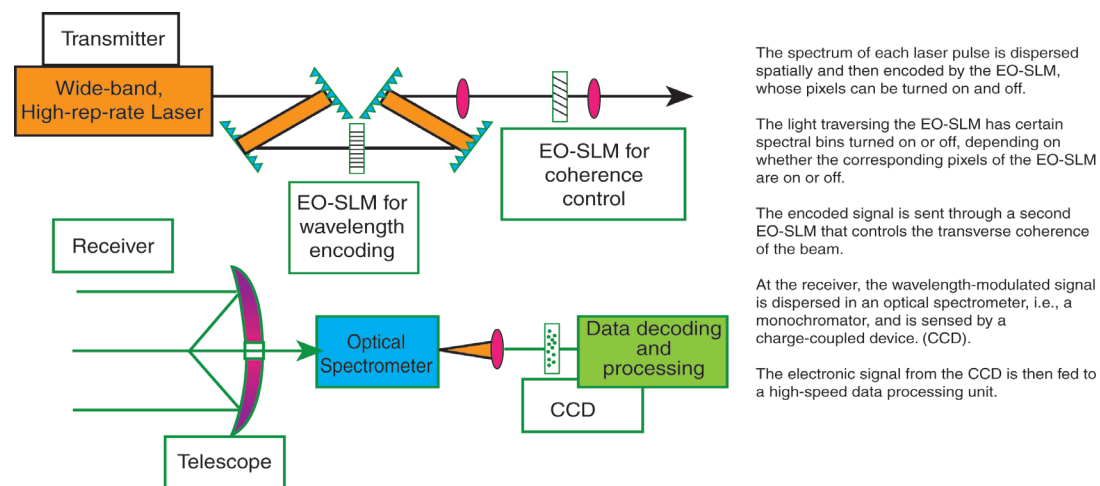


High Data-rate, Free-space Laser Communication Based on Frequency Encoding of a Partially Coherent Beam

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In this paper we present a new concept of a free-space, high-speed optical communication (FSOC) system based on spectral encoding of radiation from a broadband, pulsed laser. It is known that the intensity fluctuations of a partially coherent beam in combination with a time-averaging photodetector lead to a significant scintillation reduction with the corresponding improvement of the bit error rate (BER) by several orders of magnitude. Unfortunately, the time-averaging method cannot be applied directly to gigabit data rate communication. The main limitation of this method is related to the requirement that the correlation time between different spatially coherent spots be shorter than the response time of the photodetector. We propose to extend the technique of scintillation suppression, based on time averaging of a partially coherent beam, to gigabit data rate FSOC. In our approach, information is encoded in the form of amplitude modulation of the spectral components of

Fig. 1. The concept of spectral encoding of a partially coherent beam (PCB). Shown below is a schematic of the wide-band free space laser communication with wavelength encoding.



the laser pulse, which has a broad spectrum. To examine the intensity fluctuations of a partially coherent beam under the conditions of strong turbulence, we developed an asymptotic method for solution of the kinetic equation for the photon distribution function. We show that, for long distances, scintillations and beam wandering can be significantly suppressed.

FSOC has data rate limitations due to atmospheric turbulence. Laser beams experience three major effects under the influence of turbulence. First, the beam phase front is distorted by fluctuations in the refractive index, causing intensity fluctuations or scintillations. Second, eddies whose size is greater than the beam diameter randomly deflect the laser beam as a whole—this phenomenon is called beam wandering. Third, propagation through turbulent atmosphere causes the laser beam to spread more than predicted by diffraction theory. Scintillations are the most severe problem and result in a significant increase of the BER and consequent degradation of the laser communication system performance. For example, a gigabit data rate communication channel cannot operate with BER of 10^{-9} over distances more than 2.5 Km, even for clear weather. Several approaches have been developed to mitigate the effects of turbulence on laser communication, including aperture averaging, partially coherent beams, adaptive optics, and array receivers. Nevertheless, scintillations continue to limit the performance of FSOC, and new approaches are needed to overcome this limitation. It is well known that partially coherent beams (beams with multiple coherent spots in their transverse section) are less affected during propagation through atmospheric turbulence than a fully coherent beam. Specifically, the additional beam spreading due to the atmospheric turbulence, the beam quality degradation, and the scintillation index are less pronounced for a partially coherent beam compared with a fully coherent beam. Recently we demonstrated the techniques of scintillation reduction based on the utilization of partially coherent beams. To form partial coherence, scientists were using a static phase diffuser. In their approach, a combination of partially coherent beams with time-averaging leads to a significant scintillation reduction with the corresponding

improvement of the BER by several orders of magnitude. Another possibility is related to utilization of a spatial light modulator (SLM). The main advantage of SLM compared with a rotating phase diffuser is that the random phase distribution at the transmitter plane could change at higher rates. As we show, higher SLM frame rate corresponds to higher data rate of the communication channel. In previous research an alternative approach was proposed that uses multiple beams with different wavelengths. This approach was experimentally demonstrated using a multiemitter beam, constructed by spatially combining outputs of several single-mode fiber-coupled diode lasers. It was shown theoretically and experimentally that the scintillation index can be substantially reduced if individual beams overlap at the detector aperture and are properly separated at the transmitter plane. At the same time, the time-averaging method cannot be applied directly to gigabit rate communication. The main limitation of the time-averaging method is related to the requirement that the correlation time between different spatially coherent spots be shorter than the response time of the photodetector. This means that the SLM must have an operating frequency, ν , that is higher than the bandwidth of the photodetector, corresponding to its inverse response time $\nu \gg T^{-1}$. Since the photodetector bandwidth must be higher than the data rate of the communication channel $\nu_{\text{com}}, T^{-1} \gg \nu_{\text{com}}$, the highest data rate is limited by the highest frequency of SLM, $\nu \gg \nu_{\text{com}}$. To date, the highest frequency SLMs based on multiple quantum wells (MQW) can only operate at frequencies up to tens of MHz.

We propose to extend the technique of scintillation suppression, based on time averaging of a partially coherent beam (TAPCB), to gigabit rate FSOC. Our idea is to combine TAPCB with a spectral encoding technique. Originally, spectral encoding was applied to fiber optics communication for code-division-multiple-access. In this method, information is encoded in the form of amplitude modulation of the spectral components of the laser pulse, which has a broad spectrum. For long-distance communication, the broad-spectrum light source could be a Ti:sapphire laser. For short-distance communication it could be an LED as

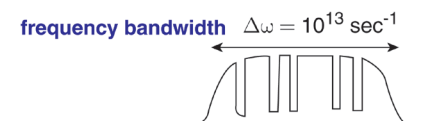
well. Each pulse or sequence of pulses (depending on the averaging response time of the photosensor) can contain kilobits of data. If the pulse repetition rate is about 1 MHz, then the transmitted data rate is gigabits per second. SLMs based on MQW technology with a frame rate of several MHz are now available.

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1) PCB reduces the scintillations
(but requires some time for averaging ~ 1 ms)
One cannot see a time domain for encoding the information!

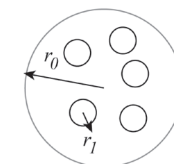
2) Spectral encoding provides high bit rate



Pulse duration ~ 10^{-10} s
Pulse repetition rate ~ 30 MHz
Encoding density ~ 10^3 bit per pulse
Frame rate of the encoding spatial light modulator 10 MHz
Bit rate ~ 1 Gb/s
 r_0 = beam radius
 r_l = coherence radius
 I = intensity of laser beam

Scintillation index

$$\sigma = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$



Parameters (example):
 $r_0 \sim 5 \text{ cm}$, $r_l \sim 0.1 \text{ cm}$

$L \sim 10 \text{ km}$

Fig. 2. Schematic of the wide-band free space laser communication with wavelength encoding.

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